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Quantum Communications Systems

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14. ABSTRACT
This project supported research activities for making quantum-enhanced communications and metrology practical. The strategy was to develop robust photonic quantum states and sensors serving as an archetype for loss-tolerant information acquisition beyond the standard quantum limit, as well as in finding practical sensing applications outside the laboratory for detecting objects in situations where power-limited illumination is critical.
Support from the US Air Force has allowed the University to establish integrated photonics as the most promising candidate for a robust implementation of quantum-enhanced optical sensors. In such a compact architecture, the challenge of achieving low-loss regime can be realistically met: convincing demonstrations of the viability of this strategy has been undertaken within the scope of this project. We have also been efficient in investigating fundamental issues of quantum metrology, establishing a general framework for understanding more complex scenarios, such as lossy parameter estimation, and joint measurements of multiple parameters.
Investigations have fostered a novel approach which will inform our future researchers: the adoption of sensing networks in which *quantum memories* act as key devices. Their role will consist in both reconfigurable devices in sensing networks, as well as in synchronization elements of multiple single-photon sources, allowing, even with current devices, a dramatic enhancement in the number of photons realistically available in the experiment.

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AFOSR project "Quantum Communication Systems"

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Overview

This document summarises the main achievements on the project "Quantum Communication Systems". The EOARD funding, which started on April 1st 2009, supported research activities toward realizing practical quantum-enhanced communications and metrology. Our strategy consisted of developing robust photonic quantum states and sensors serving as an archetype for loss-tolerant information acquisition beyond the standard quantum limit, as well as identifying feasible sensing applications for detecting objects in situations where power-limited illumination is critical.

Support from the US Air Force has enabled us to establish integrated photonics as the most promising platform for implementation of quantum-enhanced optical sensors. In this compact architecture, the challenge of reaching the low-loss regime can be realistically met; convincing demonstrations of the viability of this strategy have been undertaken within the scope of this project. We have also studied fundamental issues of quantum metrology, estabilishing a general framework for understanding more complex scenarios, such as lossy parameter estimation, and joint measurements of multiple parameters.

Our investigations have fostered a novel approach which will inform our future research projects: the adoption of sensing networks in which *quantum memories* act as key devices. Their role will consist in both allowing active reconfiguration of sensing networks, and in synchronisation elements of multiple single-photon sources. Such synchronisation allowing, even with current devices, a dramatic enhancement in the number of photons realistically availble in the experiment.

Because of the high quality of its results, and the innovative potential of the new framework that it helped to construct, the impact that this EOARD project has had on the state of the art of quantum-enhanced technologies can be judged to be extremely positive.

Work Package 1: Experimental investigation of noise-resistant states of light for precision measurement

WP1.1: Evaluating resources for real-world quantum precision measurement

Quantum metrology is aimed at the exploitation of quantum resources to enhance the precision with which measurements may be achieved. That such advantages are possible has been known for quite some time. Realizing such advantages in practice, however, poses considerable challenges. The quantum enhancement depends upon the preparation of particular non-classical states. One of the most common states in this family are the so called *N00N* states, the preparation of which scales unfavorably with N. Even though such states offer the largest scaling advantage in the ideal lossless case, such advantage is rapidly degraded in the presence of even low loss. One is then forced to adopt post-selection of the sensor output and to apply classical post-processing to demonstrate a quantum signature. However, this is insufficient to demonstrate increased precision beyond the classical limit and further information must be included to accurately compare quantum and classical strategies.

To investigate genuine quantum-enhanced precision measurement, we experimentally examined a quantum sensor based on optical interferometry [1]. We evaluated the resources, in terms of number of trials and photons, required to reach a given precision when estimating the differential phase accumulated by two optical modes. Limits to this precision were analysed using Fisher information and quantum Fisher information and compared with other common measures of enhancement such as super-sensitivity [2]. When experimental imperfections are present, we showed that quantum enhancement can be overestimated by improper resource accounting. In particular, a common error is to neglect the channel transmission, source, and detection efficiencies. We showed that improvement in state preparation and detection efficiencies are necessary to unambiguously demonstrate quantum enhancement in phase estimation, and set quantitative benchmarks (investigated in WP 2) for these. The requirements are highly demanding, yet within the capability of emerging technology. They require a compact architecture, where the loss between different components can be optimised and kept stable: these considerations lead us naturally into considering the route of integrated structures as the most efficient platform for realising quantum advantages in metrology.

As a complementary investigation, we have explored the possibility offered by more general techniques for detection. Accessing the full information content of photons requires in fact to address their particle- or wave-like behaviours at will. We have demonstrated the full capabilities of a tuneable detector, which can be operated in both regimes, by means of quantum detector tomography [3]. In order to accomplish such characterisation, we have developed new tools for quantum tomography able to bear with the large number of parameters necessary for describing our system. Beyond the intrinsic interest of the device, our findings go in the direction of characterising large quantum systems, such as multi-node networks of sensors.

WP1.2: Integrated quantum sensing

In a practical quantum sensor, the loss at the interface between different stages (source, channel and detection) is not negligible. In fact, if the system is not designed carefully, the interfacing loss will nullify all the improvement in source and detection efficiency. An ideal solution is a modular integrated photonics platform [4, 5], which provides good mode-matching throughout the system. We followed the chain of state generation, manipulation and detection to study the key requirements for and issues surrounding each [6]. We have also shown the procedure to construct programmable devices which are robust to fabrication imperfections, and demonstrated techniques for characterizing optical elements in an integrated photonic device. For quantum advantages to be achieved, the manipulation of multi-photon states in complex sensing networks will be necessary: we have achieved a major step in this direction by showing three-photon of quantum operation three coupled on-chip interferometers [8]. We have introduced a new scheme to verify quantum behaviour, using classically characterised device elements and hierarchies of photon correlation functions, which certified that the operation of our device was inconsistent with both classical and bi-separable quantum models. These results clarify the potential of photonic circuits for quantum sensing and metrology.

Complete control of the fabrication of waveguide structures is essential for realising complex circuits, and for mode-matching at the interfaces between elements. In collaboration with the group of Prof. M. Booth in Oxford we have developed an improved technique for fabrication in bulk materials by femtosecond laser writing [7]. We allow for beam shaping during the writing process by means of spatial light modulators. With this level of control, we have been able to fabricate waveguided photon sources in fused silica [9]. The phase matching for the nonlinear interaction necessary for pair production is achieved in elliptical guides, for which the transverse profile was chosen to induce form birefringence. This demonstration is a significant achievement in combining different components in a single, chip-scale integrated device.

Work Package 2: Theoretical investigation of robust states for precision measurement

WP2.1: Interferometry beyond the shot-noise limit

Quantum-enhanced metrology requires one to beat the best classically attainable precision in real-world devices with given resources. In the presence of loss, as well as imperfect preparation and detection events, we have developed an experimentally feasible class of quantum states and measurements that beat the standard quantum limit. This work has provided limits on the efficiencies required for the three steps of the protocol: preparation, propagation and detection. Such an exercise is essential for properly direct our efforts and resources to obtain palpable quantum enhancements in parameter estimation. Our work showed that losses in the interferometer are the least of the concerns in achievable apparatus. The actual bottleneck is the efficiency of the detectors followed by the efficiency of preparation. Our results are applicable to all quantum metrology experiments since the paradigm of our work is very general. Any effort at achieving quantum-enhanced precision must have the three steps of preparation, propagation, and detection.

Our work [10] studied the use of twin-Fock states of the form $|N\rangle|N\rangle$ in quantum metrology. We showed that these states, allied with photon-number-resolving detectors, provide precision that is close to the best possible in a lossy environment. Using techniques of classical and quantum Fisher information, we obtained the volume in the space of the three parameters η_p, η, η_d, – the preparation, propagation, and detection efficiencies – where one can beat the standard quantum limit. The scheme is most robust to propagation losses, which has been the sole kind of imperfection analyzed in the quantum metrological scenario till date. Our work shows that the roadblock lies in a different aspect of the experiment, namely detection.

Loss is generally treated as a classical parameter, which influences the evolution of the probe but contains little or no relevant information per se. This is not generally true, and there are important examples, in particular for biological systems, in which absorption is an interesing aspect of the dynamics together with a phase shift. In most situations it is hard to conceive a separate estimation of phase and loss, which leads into considering the problem of joint multiparameter estimation. This is the case, for instance, of rapid dynamical problems, for which the time it takes for a reconfiguration of the apparatus can be long with respect the characteristic time of the process. In our work [11] we have conducted an extensive theoretical investigation on the quantum limits on joint precision when estimating phase and loss in the same apparatus. We have estabished a fundamental trade-off between the precisions that can be attained for each parameter individually, and have been able to construct the quantum states achieving the best possible compromise.

WP2.1: Novel approaches to quantum-enhanced metrology

The number of photons which are nowadays realistically available to a sensing scheme is ultimately limited by the efficiency of quantum light sources. To date, all sources are probabilistic, an aspect which hinders entering a favourable regime for quantum-enhanced measurements. Our theoretical investigation in [12] has shown the advantage of incorporating quantum memories as a synchronisation device, with the potential of improving by orders of magnitude the probability of multi-photon events. Remarkably, the performance of the synchronisation protocol is resilient to imperfections of the memories, such as limited efficiency, as long as the time-bandwidth product (TBP) is large. We have developed atomic memories in caesium vapour, based on a stimulated Raman transition, that have demonstrated a TBP greater than 1000 and are uniquely suited to this purpose. Furthermore, we have shown that these memories can function as reconfigurable elements in quantum networks [13], an essential ingredient for developing adaptive sensing schemes.

The strong potential of this novel scheme is largely unexplored, and this area represents promising avenue for future research.

The general nature of our Raman memory scheme lends itself to diverse physical implementations. We are particularly interested in durable, room-temperature systems that are suitable for large-scale integration into practical technologies. Along these lines, we successfully demonstrated quantum Raman interactions in room-temperature, macroscopic pieces of diamond [14, 15]. The properties of phonon lines in diamond have allowed us to implement an interaction between our material and femtoseond optical pulses, resulting in the creation of a robust quantum superposition state involving a phonon in the diamond lattice, involving the motion of a macroscopic number of constituents. We have been able to demonstrate genuine quantum features of such collective exitations in a single diamond [14]. We have embedded two of these memories within an interferometric setup, which permitted the preparation of an entangled state of two macroscopic objects, for the first time in solid state and at room temperature [15]. In addition to its technological implications, the creation and obervation of quantum correlations between the motion of two macroscopic solids in ambient conditions is of fundamental interest, as it pushes the boundary of the quantum and classical realms.

The precision of a physical measurement is ultimately limited by quantum uncertainty principles. It can be improved by increasing the number of particles used to probe the parameter. The statistical error tends to zero then, but at a convergence speed that depends on the initial state of the system and the measurements to be performed on the system. So far, the most accurate measurements which can beat the shot noise, i.e the standard quantum limit, have been obtained with entangled states, but these are quite hard to produce experimentally. Recently, it has been shown that the quantum noise of a measurement could be reduced by introducing nonlinearities in the evolution of the probe particles [16].

We have experimentally put this theoretical breakthrough into practice by designing and implementing a robust asymmetric polarization interferometer [17]. Such a novel interferometer enables us to probe the nonlinear polarization rotation induced by self-phase modulation without the influence of cross phase modulation in nonlinear optical samples, meanwhile enables us to measure birefringence-induced polarization rotation as a reference. With high-intensity ($N \approx 10^8$ photons per pulse) and ultrafast 70-fs laser pulses laser, we performed low-noise measurements of the nonlinear coefficient of a standard optical fiber. The results show that the standard deviation scales as $1/N^{3/2}$, well beyond the standard quantum limit ($1/\sqrt{N}$) and even the Heisenberg limit ($1/N$), confirming that the nonlinear nature of Hamitonian can be a key resource for quantum-enhanced precision measurement. Our technique enables quantum-enhanced measurements at room temperature with high photon numbers, both important features for developing practical applications.

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